Analysis, Design and Simulation of a Compact Wide Band VHF High Power Tubular Band Pass Filter

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Abstract— This paper present analysis, design and simulation of a compact VHF high power tubular band pass filter terminated with capacitor. In this analysis all effects of critical distributed and lumped structures are considered. Full wave simulator (HFSS) is used to analyze and optimize the filter performance and high power analysis done to achieve high power handling. The peak power in this filter considered above 10 kW and average power of about 1200 Watt. The insertion loss of VHF BPF filter is less than 0.6 dB and 0.2 dB bandwidth is about 10 MHz at the center frequency of 220 MHz, the stop-band attenuation is more than 30 dB at 205 MHz and 235 MHz (shape factor is 30 dB/Oct), return loss is better than 20 dB and so VSWR better than 1.2 in whole pass band. Moreover, the filter is compact in size and the dimensions are 4.5 cm × 50 cm.

1. INTRODUCTION

Lumped element filters are used at microwave frequency to about 18 GHz [1]. Dimensions of theses filters are much smaller than distributed filters, which is their major advantages. However the use of larger distributed filters is suitable when insertion loss and power handling are major concern. Actually one of the most important problems of high power transmitter is harmonic radiation and the interfering effects on other communication system. Major efforts are been done to reduce the interferences. To remove the spurious radiation various filters have been presented in [2–4]. Also various type of high power filters in [5, 6] have been proposed. These filters constructed by dielectric resonator and sinusoidal quasi periodic waveguide structures. In order to solve the large dimension and power handling difficulties, semi lumped technology was used. Several filters were realized in a semi lumped approach using both air wound inductors and coaxial transmission line or surface mounted (SMT) capacitors and microstrip lines. Tubular band pass filters are narrowband semi lumped approximation of band pass filters. Significant developments have taken place since 1998 [7]. Super conductor technology and microstrip lumped element circuits has been introduced as a tubular BPF with fractional band width about 0.6% (narrowband). Of course when power handling is important, super conducting filter technology is not employed. The later method has been presented in 2006 [8], as a wide band case which is tubular filter terminated with inductor. Generally tubular filters may be classified in two categories, one defined as a tubular filter terminated with categories, one defined as a tubular filter terminated with capacitor as shown in Fig. 1 [7, 9], and other as a tubular filter terminated with inductor, which is shown in Fig. 2 [8].

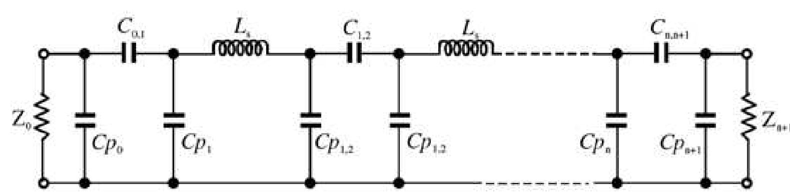


Figure 1: Semi lumped element filter terminated with capacitor [2].

In both of them each node containing a ground and all resonators are the same type. This paper present analysis, design and simulation of a VHF coaxial high power tubular band pass filter terminated with capacitor. In Section 2 basic filter designs will be introduced, filter geometry and prototype values are discussed. The realization of filter is presented in Section 3 and the physical parameters of capacitors and inductors are obtained. In Section 4 simulation and optimization of the designed filter terminated with capacitor is presented. By using the approach suggested for the study of filter terminated with inductor [8], the optimization involves computer aided optimization and full wave EM simulator. Therefore to achieve filter with high power handling and harmonic

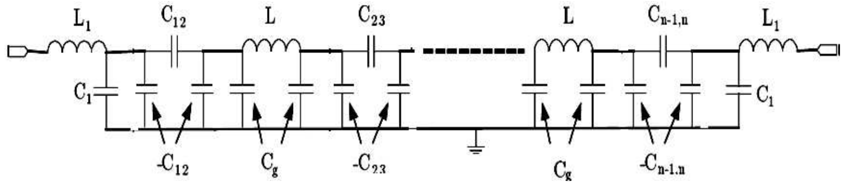


Figure 2: Semi lumped element filter terminated with inductor [8].

spurious rejection, semi lumped approach is considered. Actually the filter was realized with lumped element and transmission line segments. High power analysis is done in Section 5. In this analysis all effects of critical distributed and lumped elements are considered. Finally conclusions are drawn in Section 6.

2. BASIC FILTER DESIGN

Detailed design procedures of initial values of lumped tubular filters can be used in several texts [7, 9]. The design process of filter terminated with capacitors is summarized as follow. First typical LPF using impedance inverter (Fig. 3(a)) is transformed to corresponding BPF (Fig. 3(b)) by applying the transformation described in [10], replacing inductors L_{ai} in Fig. 3(a) with $L_{si} = (w\omega_0/\omega_c)L_{ai}$ and $C_{si} = 1/(\omega_0^2 L_{si})$ in Fig. 3(b). After that the impedance inverter values are designed based on normalized element values:

$$K_{01} = \sqrt{\frac{R_0 w\omega_0 L_S}{\omega_1' g_0 g_1}} \tag{1a}$$

$$K_{i,i+1} = \frac{w\omega_0 L_S}{\omega_1'}\sqrt{\frac{1}{g_i g_{i+1}}} \tag{1b}$$

$$K_{n,n+1} = \sqrt{\frac{R_{n+1} w\omega_0 L_S}{\omega_1' g_n g_{n+1}}} \tag{1c}$$

where w is the fractional bandwidth, ω_0 is normalized cut off frequency equal to 1 rad/s, L_S is inductor that specified by user, in this work the inductor chosen as 150 nH. Impedance inverter can use the tee of capacitors network. Then split the series capacitors (C_{Si}) of series resonators into two capacitors ($2C_{Si}$), one on each side of the inductors, negative capacitors between inductor in middle stages is observed and tee network capacitors converted to the exact equivalent *pi*. But negative capacitors at the input and output termination couldn't be realized, therefore use transformation was described in [4]. Finally the equivalent circuit of BPF is shown in Fig. 3(c).

The values of series capacitors and shunt capacitors of input and output pi networks, C_{01} and $C_{n,n+1}$ are achieved respectively.

$$C_{01} = \sqrt{\frac{Z_0\left(2\omega_0 C_S K_{01}\right)^2}{Z_0^2 + \left(2\omega_0 C_S K_{01}\right)^2} \cdot \frac{\left(1 + Z_0^2\omega_0^2 C_{X0}^2\right)}{Z_0\omega_0^2}} \tag{2}$$

$$C_{P0} = C_{X0} - C_{01} \tag{3}$$

$$C_{P1} = \frac{1}{\omega_0}\left[\frac{Z_0^2\left(2\omega_0 C_S\right)}{Z_0^2 + \left(2\omega_0 C_S K_{01}\right)^2} - \frac{\omega_0 C_{01}\left(1 + Z_0^2\omega_0^2 C_{P0} C_{X0}\right)}{1 + \left(Z_0\omega_0 C_{X0}\right)^2}\right] \tag{4}$$

In this equations C_{X0} is chosen as that capacitors of C_{P0} and C_{P1} be realizable and is better to be equal. Therefore coupling and shunt capacitors, $C_{i,i+1}$ and $C_{Pi,i+1}$ between inductors, easily achieved by:

$$C_{i,i+1} = \frac{\left(\frac{2C_S}{1-2C_S\omega_0 K_{i,i+1}}\right)^2}{\frac{4C_S}{1-2C_S\omega_0 K_{i,i+1}} + \frac{1}{\omega_0 K_{i,i+1}}} \tag{5a}$$

$$C_{Pi,i+1} = \frac{\frac{1}{\omega_0 K_{i,i+1}}\left(\frac{2C_S}{1-2C_S\omega_0 K_{i,i+1}}\right)}{\frac{4C_S}{1-2C_S\omega_0 K_{i,i+1}} + \frac{1}{\omega_0 K_{i,i+1}}} \tag{5b}$$

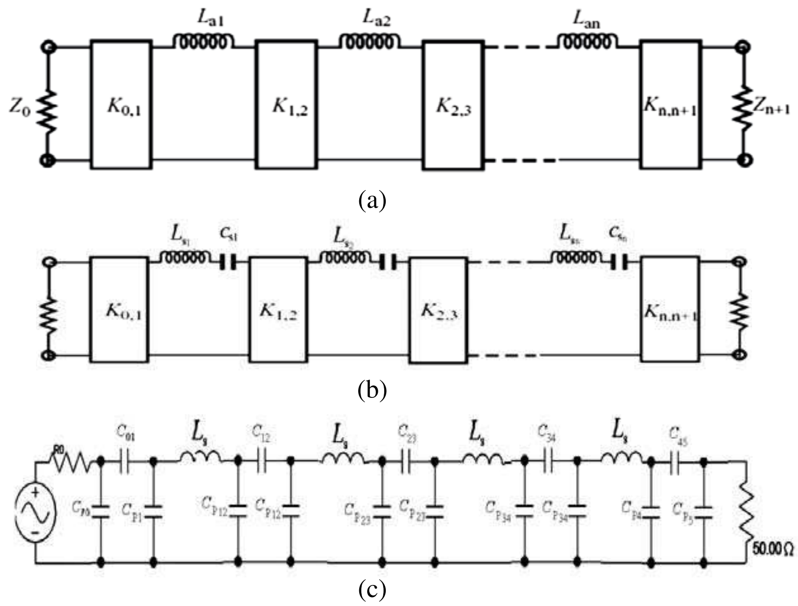


Figure 3: (a) Shunt-C coupled series resonator band pass filter, (b) band pass filter using admittance inverter, (c) equivalent circuit of tubular BPF.

Therefore all parameters of equivalent circuit are obtained. Where C_S is series capacitor in series resonance circuit and it is given by:

$$C_S = \frac{1}{\omega_0^2 L_S} \tag{6}$$

In this paper it's desired to design a filter with band ripple 0.01 dB, fractional bandwidth of 5% and a shape factor that cause 30 dBc at 10 MHz out band offset. Based on the previous equations, the obtained values of reactive elements are listed in Table 1.

Table 1: The lumped element values of equivalent circuit obtained by design.

Reactive lumped element	**Designed values**
$C_{P0} = C_{P5}$	3.32 (PF)
$C_{01} = C_{45}$	3.98 (PF)
$C_{P1} = C_{P4}$	3.32 (PF)
L	150 (nH)
$C_{12} = C_{34}$	0.6925 (PF)
$C_{P12} = C_{P34}$	6.35 (PF)
C'_{P12}	6.35 (PF)
C_{23}	0.506 (PF)
C_{P23}	6.5 (PF)

3. REALIZATION OF THE FILTER

For realization of the filter in coaxial form, physical parameters of distributed and lumped element should be specified. Consider the topology of four orders Chebyshev band pass filter in Fig. 4, realized by five series coupling capacitors and four resonators that constructed by lumped and distributed element. All inductors are the same value and can be chosen optionally. These inductors have been realized by wire wound air core inductors, shunt capacitors by the gap between metal disks and outer metal tube, and coupling or series capacitors by dielectric gap between cross sections of metal disks as it is shown in Fig. 5. This figure illustrated the reactive elements which are used for practical implementation of this filter. Important criteria in choosing reactive elements such as inductors, dielectric gap and air gap is considering average and peak power handling which is discussed in Section 5. As known coaxial capacitors consist of two cylinders sharing the same axis.

This coaxial capacitor will have inner radius of r_d and outer radius of b. Also the distance between plates is the distance between two radiuses $t_1 = b - r_d$. In the case of which distance of between the inner and outer radius is small, the capacitance of coaxial capacitor is equal to parallel plate capacitor that is given by (7):

$$C_{\text{Parallel}} = -\frac{2\pi\varepsilon l}{\ln\frac{b}{r_d}} = \frac{2\pi l\varepsilon b}{b - r_d} \approx \varepsilon\frac{A}{t_1} \tag{7}$$

where, A is the area of outer radius of coaxial capacitor. Series capacitors are:

$$C_{\text{Sereies}} = \varepsilon\frac{S}{t_S} = \varepsilon_0\varepsilon_r\frac{\pi r_d'^2}{t_S} \tag{8}$$

where t_S distance between round metal plates and $r'_d = r_d - r_s$ that r_s is radius of dielectric shaft cross from elements. Serial inductors are given by:

$$L = \frac{(Rn)^2}{10l_{\text{sim}} + 9R}\,(\mu\text{H}) \tag{9}$$

R, l_{sim} are mean radius of core and length of coil (in inch), n is number of turn wound wire. For realizing of physical reactive elements as Table 1, primary parameters values have to choose optionally. Chosen diameter of copper wire, length of wound wire, diameter of Teflon core, diameter of aluminum disks and diameter of shaft dielectric, are listed in Table 2. Then by using (7)–(9), length of metal disk of shunt capacitors, dielectric thickness for series capacitors and number of wound turn are found.

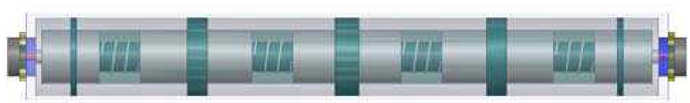
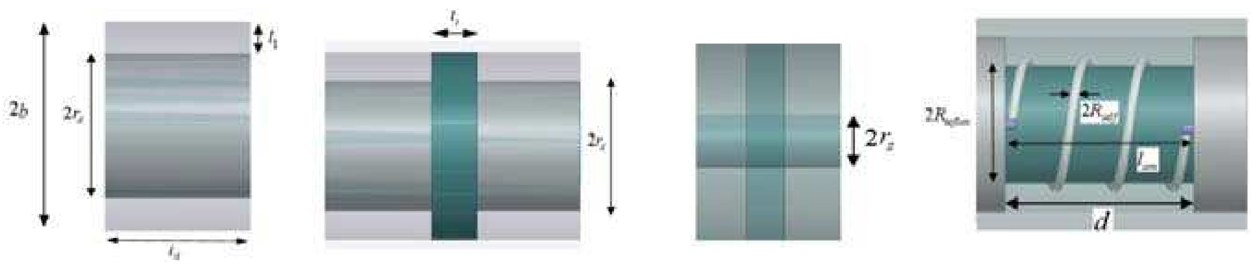


Figure 4: Configuration of a semi coaxial band-pass filter.



(a) (b) (c) (d)

Figure 5: Physical realization of (a) reactive element, (b) shunt capacitor, (c) coupling series capacitor, (d) series inductor.

Table 2: The primary physical dimensions of elements have been chosen optionally by user (mm).

parameter	**Values (mm)**
Diameter of copper wire ($2R_{\text{self}}$)	1.6
Length of wound wire (L_{sim})	30
Diameter of Teflon core ($2R_{\text{teflon}}$)	20
Diameter of coil of core (R)	$2R_{\text{teflon}} + 2R_{\text{self}}$
Diameter of aluminum disks ($2r_d$)	35
Thickness of air (t_1)	8
Diameter of axial dielectric (r_s)	8

4. SIMULATION AND OPTIMIZATION OF THE DESIGNED FILTER

4.1. Optmization Procedure

After design and calculation of physical parameters, an electromagnetic simulation is done. To optimize the filter, due to the large number of parameters, it will be optimized by using electromagnetic simulator and computer aided design method. At the first step, all designed values of lumped element circuit of BPF, are simulated by ADS Agilent and then the frequency response is tuned. After that, designed n-order filter, will be divided into $2n+1$ stages that consists pi network capacitors or series inductors. In optimization procedure, the result of EM simulator (Ansoft HFSS) (for different physical parameters) will be compared with design analysis of ADS, to verify each other, thus exact values are determined. In this sequence, first stage will be optimized separately, and then the new stage will be added and optimized when the values of first stage remain steady and the process of increasing stage continues until $(n+1)$ stage because of symmetrical structure of the filter. In addition, all metal disks have the same radius and thickness of dielectric sheet between metal disk and outer tube is constant along the filter so, at each step of optimization, maximum two or three parameters are changed and optimized.

4.2. Simulation Result

As described in the previous sections EM simulating by HFSS software is done. Usually frequency response of the filter structure is different from the design demands. So as mentioned, optimization should be performed. Each stages of filter one by one added to first stage. Variable parameters are length of wound wire, number of turn and length of disks. Because of symmetrical structure the processes of optimization for 6th to 8th stages are not required. Finally EM simulation is done for the whole filter by adding last stage (9th stage), (Fig. 6). As it is shown in Fig. 6, full wave analysis of the filter confirms the designed filter and performance of the full wave simulation of the complete structure, including coaxial connector and dielectric loss tangent. The filter has a center frequency of 220 MHz, 0.2 dB bandwidth of 10 MHz, insertion loss of about 0.6 dB, better than 30 dBc rejection in 10 MHz offset from the 0.2 dB bandwidth and a return loss better than 20 dB.

5. POWER-HANDLING ANALYSIS

It's necessary to use LPF or BPF filter at Output of high power microwave transmitters and receivers to prevent of harmonics in transmitting and interferences in receiving. So microwave filter in this application must be capable to handle the high power signals from high power amplifiers. Average power and peak power should be considered in high power handling. For average power, critical point is inductor, where the wire of inductors must have enough diameters to tolerate the current in the filter. The average input power is 1200 Watt and the input impendence is 50 Ohm. Thus, the average current is 5 A. Another important factor is breakdown that can destroy the filter component and performance by arcing. Breakdown voltage limit depends on RF circuit, structure geometry and RF frequency. To analysis of electrical field inside the filter, HFSS is used

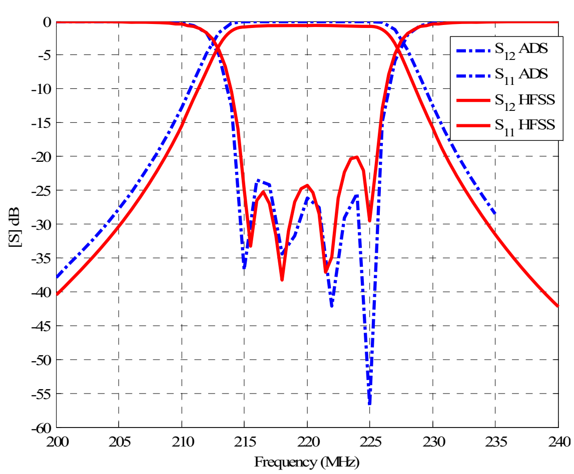


Figure 6: Simulated frequency response of the experimental band pass filter ((solid & dot-dash lines) on HFSS-ADS respectively).

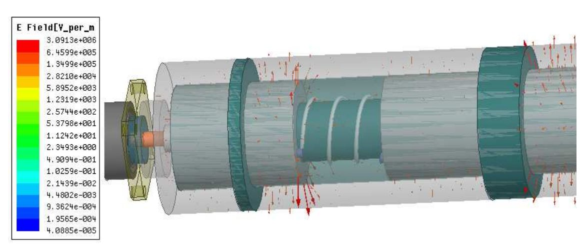


Figure 7: Vector E-field strength (V/m) across the filter in frequency 220 MHz.

as a simulator. Actually the voltage breakdown is influenced by the geometry and the dielectric strength. So for high power analysis, the critical parts across the filter should be considered. Two methods are used to enhance the breakdown voltage of the filter. The first one is using wider air gaps between disks and outer metal tube that can enhance breakdown voltages and the second method is using the thin dielectric sheet in air gaps. The Teflon (PTFE) in the gaps that can enhance the voltage breakdown to 15.74e6 v/m. A vector plot is used arrows to illustrate the magnitudes and direction of electrical field which is shown in Fig. 7. It can be seen that the electric field strength in all over the filter is less than breakdown voltage in air (3e6 v/m) and Teflon (PTFE) with input power of 10 kW.

6. CONCLUSION

In this paper, a compact VHF semi lumped high power band pass filter is investigated based on the traditional tubular theory of the filter terminated with capacitors and Chebychev method. Analyzing of all effects of critical distributed and lumped structures were considered. The high power analysis of the filter in the realization structure was done. In the final simulation the complete practical structure were considered and optimization with the full wave analyzing software (Ansoft HFSS) were done. It is confirmed that the filter topology provides much better high power handling capability (about 10 kW). The final result are very close to design goal and filter has a center frequency of 220 MHz, 0.2 dB fractional bandwidth of 10 MHz, insertion loss of about 0.6 dB, better than 30 dBc rejection in 10 MHz offset from the 0.2 dB bandwidth, a return loss better than 20 dB and has a compact size (total length of 50 cm). Based on all experimental considerations in the full wave analysis and final results of the filter, this filter can be fabricated and use in many application which the presented in the feature works of the authors.

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